USDA FOREST SERVICE
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ENERGY&WOOD from intensively cultured plantations: research and development program

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North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

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from intensively cultured plantations: research and development program

TABLE OF CONTENTS

	Page
Background	2
Selection of promising species	5
Stand establishment methods	6
Fiber and energy yields in response to spacing and harvest cycles	8
Yield response to nutrient and moisture regimes	10
Effect of crown architecture and canopy density on yield	11
Physiological factors influencing yield	13
Raw material quality of intensive culture trees	14
Diseases of intensive culture species	17
Insect problems in intensive culture	18
Design of mechanized equipment for intensive culture systems	19
Cost of producing wood for fuel and fiber	20
Industrial cooperators	21
Publications	24

The first small plot experiments were established in 1970 to test the growth of various Populus *clones and the effect of spacing on yield.*

BACKGROUND

The Maximum Yield Work Unit was established in 1971, by the North Central Forest Experiment Station in response to concerns expressed by both industrial foresters and researchers. Industrial foresters realized that new systems for growing more fiber on less land must be explored because of escalating fiber demand, increasing demand for recreation and nonforest uses of forest land, rising land prices and tax rates, and increasing harvest and transportation costs.

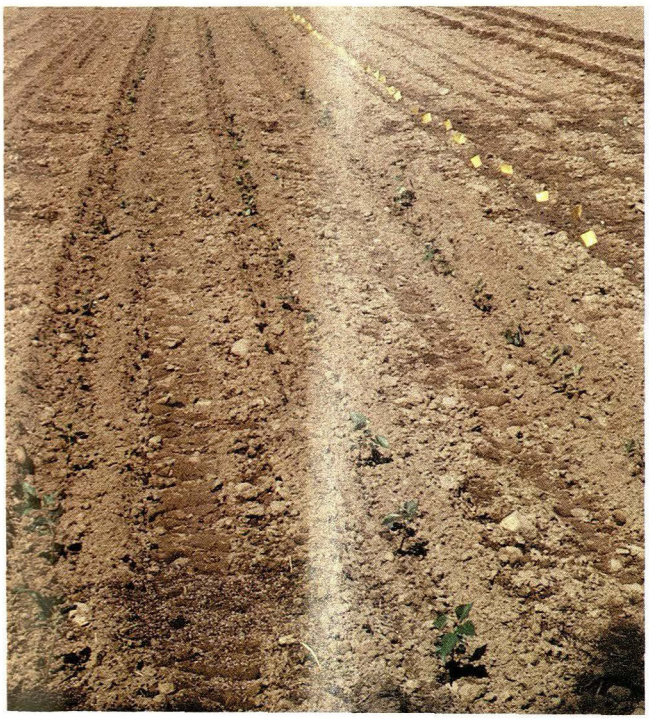
Forestry researchers realized that much basic genetic, physiological, and cultural knowledge could be applied if environmental conditions for growing trees could be more closely controlled as in agriculture. Research was begun to select promising species, establish intensively cultured plots, explore new harvesting methods, evaluate pulping qualities of the fiber, and assess the economic viability of this system. This program used a systems approach, with researchers from many different disciplines working together.

In 1976, the program was expanded to incorporate both developmental and basic research, active cooperation with industries, and the collaboration of scientists from different disciplines in a systems approach. The research team now includes silviculturists, physiologists, an ecologist, geneticists, a soil scientist, hydrologist, a wood technologist, a pathologist, an entomologist, an engineer, and an economist.

Supplemental funding from the Department of Energy since 1977 has enabled researchers to accelerate progress in several problem areas, with emphasis placed on the development of methods to plant trees and ensure their early survival. Establishment is the most critical problem in the short-rotation-intensive-culture (SRIC) system because larger research studies or large-scale industrial plantations cannot be established until the technology to successfully plant hardwood stands has been developed. Although practices for planting softwoods were developed long ago, no system for consistently establishing plantations of hardwood forest trees in the upper Midwest has been developed (except for the shelterbelt plantings of the northern Plains). The problems in large-scale planting operations are often different from those normally encountered in small plot experiments, and the additional funds have enabled researchers to provide

information to help industry establish larger pilot-sized plantations.

More than 10 acres a year of intensively cultured plantations are being established at the Harshaw Experimental Farm near Rhinelander, Wisconsin. Emphasis is on developing cultural practices and mechanized equipment suitable for operational plantation management.



The USDA Forest Service's Maximum Yield of Wood and Energy from Intensively Cultured Plantations Research and Development Program includes two Research Work Units as well as scientists from other Research Work Units within the North Central Forest Experiment Station. Research problems, objectives, and results will be presented separately in this report for each problem area, although this does not accurately represent the overlap and interaction between problem areas due to the complex set of factors that determine biomass yield.

Briefly, the SRIC concept is that plantation biomass yields can be greatly increased by using genetically superior planting material and optimizing field environmental conditions. Generally, hardwoods have been tested more thoroughly for intensive culture systems because of their rapid juvenile growth and their ability to sprout from the stump after they are harvested, thus eliminating the need to replant the trees.

The establishment of intensive culture plantations with most species in any region of the United States will likely include essentially the same kinds of operations, although the precise nature of these operations will vary greatly by species and site. Many of these concepts are more typically termed "agricultural" rather than "silvicultural" in nature.

One of the most critical problems in establishing the short-rotation-intensive-culture system is weed control. Weeds are a serious competitor during the first 2 years, and research in weed control methods has recently been expanded.

First, the land must be cleared and plowed to eliminate other plants and to make the site suitable for planting and cultural equipment (i.e., abandoned farm land is well suited). Seedlings or cuttings are planted with mechanical planting equipment at varied distances from a few centimeters to several meters within the rows that are from 1 to several meters apart. The first growing season is critical to the survival of the small trees, and plantations must be kept free of weeds either by cultivating, planting a cover crop between the rows, applying an herbicide, or other means. Each growing season the trees are provided optimal amounts of nutrients and water by fertilizing and irrigating. Diseases and insect pests are also controlled.

After 6 to 10 years, at a time when the trees reach near-optimal biological growth, the trees could be harvested using specially-designed harvesters. The wood will likely be chipped and used for energy, pulp, reconstituted wood products, feed, chemicals, or any combination of these products. In the spring following harvest, several new stems will sprout from each cut stump (coppice), and these will become the next crop of trees.

Irrigation is one of the cultural practices being studied in this research program. More precise information about the quantity and timing of irrigation is still needed.

SELECTION OF PROMISING SPECIES

These plots were established in 1974 to test the performance of different Populus *clones. Note the differences in growth rate of these clones after 3 years under similar intensive culture conditions.*

Research Problem

The characteristics of high-yielding trees for intensive culture are significantly different than those for conventional forestry. Selected species must be biologically efficient to take full advantage of the optimized conditions of intensive culture.

Research Objectives

Promising species and clones must be screened for a wide range of biological and physical properties. Initial tests include growth rate, response to different spacings, response to water and nutrient management, sprouting ability, insect and disease resistance, wood quality, and adaptation to regional climatic conditions. As results from physiological studies of crown architecture, photosynthesis, and translocation of photosynthetic products are obtained, they will be included in genetic selection and breeding programs.

Research Results

The genus *Populus* (poplars and cottonwoods) was selected for the early experiments because of its rapid juvenile growth, ease of hybridization, vegetative propagation, and the vast amount of information already known about its growing requirements. In 1971, 30 *Populus* hybrid clones were tested in field plots at Rhinelander, Wisconsin, and Ames, Iowa. Fourteen of these have been selected for further testing under various intensive culture techniques. Other species tested included jack pine, (*Pinus banksiana*), larch (*Larix laricina*), alder (*Alnus*), and green ash (*Fraxinus pennsylvanica*).

Rapid laboratory screening tests have been conducted using physiological and morphological characteristics, such as net photosynthesis rate, production of enzymes controlling nitrogen uptake and metabolism, branch angle, and leaf orientation on branches.

Controlled-environment chamber experiments were also completed for 25 Populus clones using 3 different combinations of growth period and temperature. After comparing total biomass, leaf weight, stem weight, height, and leaf number at 8 weeks, 14 clones were recommended for field testing.

STAND ESTABLISHMENT METHODS

Weed competition is one of the most serious problems in establishing hardwoods for intensive culture. In field experiments, the herbicide "Roundup" was found to keep stands almost free of weeds.

Planting low lying leguminous cover crops may be an effective way of simultaneously providing soil nitrogen and controlling weeds. White Dutch clover shown here prevents the growth of taller weeds that might otherwise shade and compete with the hybrid poplar cuttings, but is also competitive with the trees.

Research Problem

The survival of trees during the critical first 2 years is primarily determined by vigor of the planting stock; adequacy of site preparation, fertilization, and irrigation; and control of competing weeds. Because early site occupation is desired for intensive silviculture systems, high survival of planted trees is important. Stand establishment techniques have not been well developed for hardwood plantations, although application of agronomic and horticultural methods offer promise.

Research Objectives

It is expected that plantation establishment methods for *Populus* clones will be developed during the next 5 years to attain a survival rate of 90 percent. Methods for site preparation; mechanical, biological, and chemical weed control; and mechanization of cultural operations will be studied. In particular, conventional farming techniques will be tested. Alternative vegetative propagation systems will be studied, including methods for collecting and storing cuttings, methods for obtaining plants from greenhouse stock plants, methods for stimulating the rooting of clones that are difficult to root, and possibly systems for establishing cuttings in containers.

Research Results

Studies began in 1978 to test the effectiveness of 245 combinations of methods of weed control in both spring and summer plantings were evaluated after the first year. The best site preparation methods were chisel plowing or a combination of moldboard plowing to 9- to 10-inch depths followed by disking and spike-tooth harrowing. Crownvetch and birdsfoot

Weeds may be controlled by mowing, a method that is widely used in orchards.

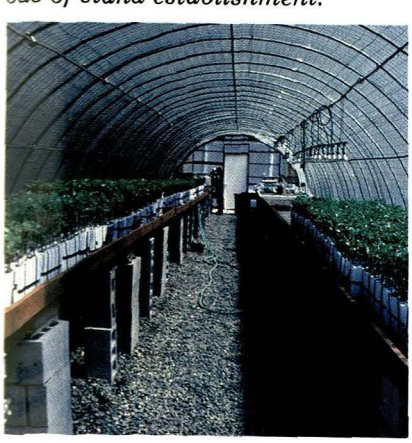
trefoil, both leguminous nitrogen-fixing plants, were the most effective cover crops for stimulating tree growth during the first year, but were not effective when evaluated the second year. "Linuron" and "Roundup" herbicides were the most effective herbicides when no other weed control method was used. A combination of a crownvetch cover crop together with herbicide "Treflan" was slightly better than any other weed control treatment.

One year of data is by no means conclusive, and the above-average rainfall during the growing season may have produced different results than a similar experiment in a drier year. However, this study provides preliminary information regarding promising site preparation and weed control methods that should be tested in larger plantings.

The optimal propagation method may vary with the time of planting. In this study, soaked and unsoaked hardwood cuttings had the best height growth and survival for all planting dates. Rooted hardwood cuttings in "Tubepak" containers provided no advantage in either survival or height growth. Bare rooted tip cuttings performed poorly for all planting dates.

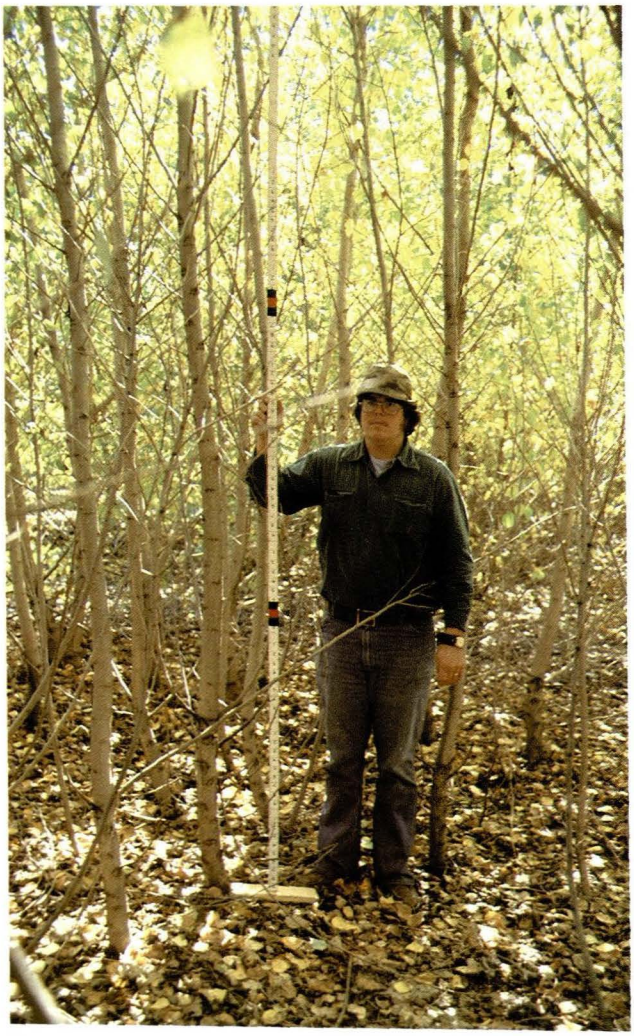
Some of the fastest-growing *Populus* clones, in particular, *P. alba L.* x *P. grandidentata* Michx. hybrid (Crandon), are difficult to establish vegetatively—less than 50 percent of the cuttings rooted using normal greenhouse practices. However, rooting greenwood tip cuttings in greenhouse flats at temperatures of 76° to 85°F provided 70 to 100 percent rooting success, faster rates of root elongation, and less mortality from fungal and bacterial infections. Hormone treatments increased rooting success and number of roots per cutting, but hormone concentration was less important than temperature.

Containerized Populus *cuttings are grown in the greenhouse in preparation for planting. The survival rate of these rooted cuttings will be compared to that of unrooted cuttings to determine the most effective methods of stand establishment.*



New greenhouse methods such as hydroponics are being tested for mass production of rooted greenwood cuttings. This method may be more economical for establishing cutting orchards because it uses less greenhouse space than containerized stock.

FIBER AND ENERGY YIELDS IN RESPONSE TO SPACING AND HARVEST CYCLES



Trees planted at close spacings will quickly occupy the entire site. After 6 years, essentially no sunlight will reach the ground in this stand, which was planted at 0.6 m x 0.6 m spacing.

Research Problem

One of the keys to maximizing fiber and energy production in forest stands is to optimize cultural practices— the spacing and rotation age for the selected species and clones. In particular, information is needed on the efficiency of capturing solar energy by plants and the energy relations in intensively cultured plantations.

It is known that closely spaced stands (1×1 m or less) fully occupy the site within a few years; therefore, essentially all the sunlight is intercepted by the leaves before it reached the ground. Closely spaced stands also attain maximum mean annual production early in the rotation, but the competition between trees begins to reduce the annual biomass production per tree. In addition, closely spaced stands are more expensive to establish and it is doubtful that these additional costs can be recouped through higher yields. Because the mean annual production is closely related to the stand's leaf area index (leaf surface area per unit land area), it appears that early optimization of leaf area may increase yields, much as cultural systems to optimize leaf area index in agriculture have been successful.

Research Objectives

Preliminary research on small plots to determine the effect of spacing and rotation age on yields has almost been completed, and researchers are currently evaluating the most promising spacings and rotation ages on yields of larger field plots. From the results of specific studies they will establish mathematical relations between total tree dry weight and easily measured variables such as diameter and height, determine effects of spacing on dry weight distribution among tree components, and determine leaf biomass and leaf area index with respect to various yields. The optimal combinations of spacing and rotation will be studied for the maximization of fiber and energy production in stands of *Populus*, alder (*Alnus glutinosa*), jack pine, and larch. The distribution of major nutrients within the stands will be studied and effects of frequent harvesting on nutrient budgets will be determined.

An integral part of biomass production studies is determining the efficiency of solar energy utilization by plants. This energy data is particularly needed for evaluating systems in which tree plantations would be utilized as an energy source. By comparing the heat of combustion of harvested biomass to the energy requirements for intensive culture, the net energy gains will be assessed.

Research Results

Early field tests of closely-spaced *Populus* 'Tristis' hybrids showed that total aboveground biomass yields could exceed 20 dry tons/ha/year for 4-year-old

trees grown under intensive culture. Tree growth and competition information from these plots was then used to model stand growth and project yields for 10- to 25-year rotations. The table below summarizes both the observed yields on small plots, and the projected yields of stems and branches (Ek and Dawson 1976):

Stem-Branch Biomass Yield

Item	Spacing			
	0.23 m	0.30 m	0.61 m	1.22 m
	----------*t/ha/yr*----------			
Actual yields:				
4 years	11.3	13.0	7.5	—
Projected yields:				
10 years	17.0	16.5	16.0	15.5
15 years	—	—	—	29.0
20 years	—	—	—	36.0

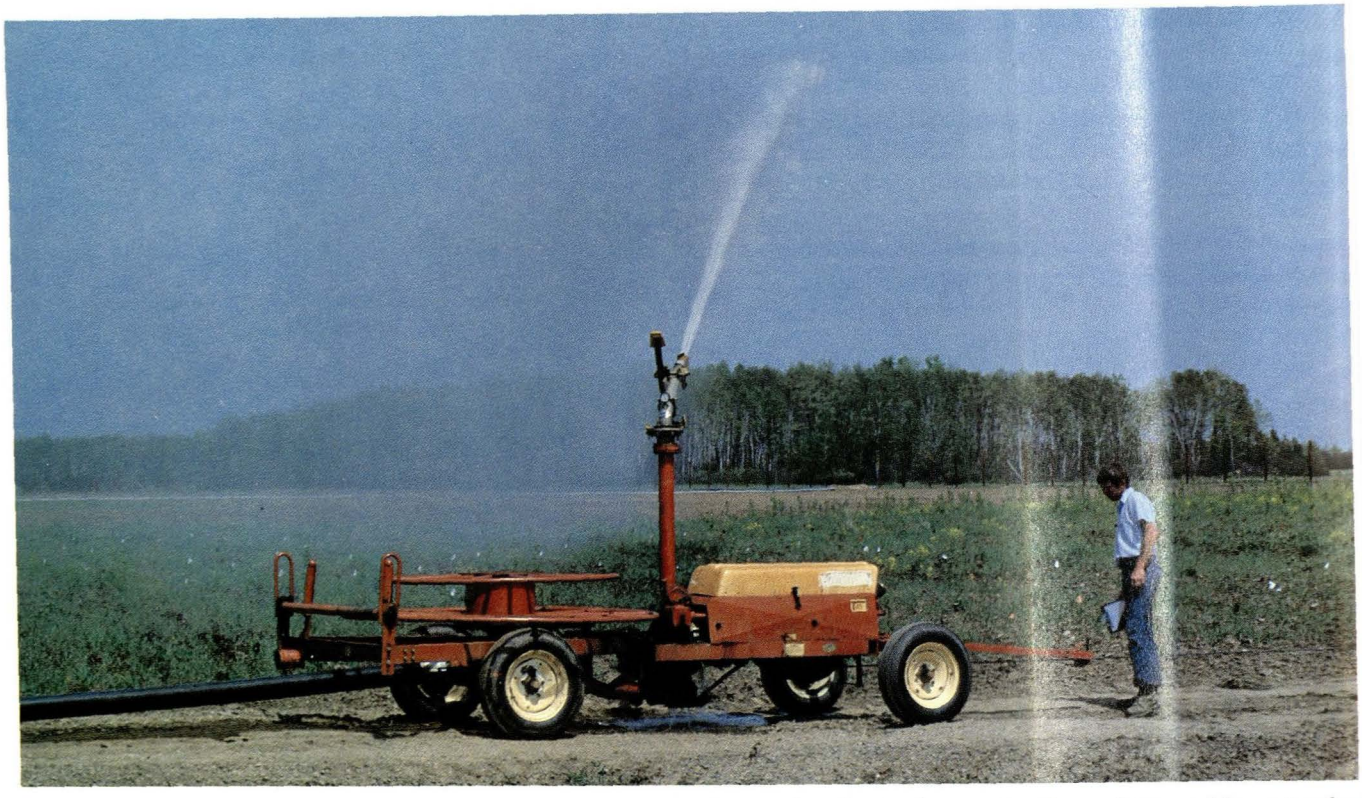
Field studies have shown that 1.0 m spacings will have the same annual yields as 0.23 m spacings after 4 to 6 years. Therefore, field tests of selected clones have now been established to test spacings up to 2.0 m and the effects of various cultural practices on those spacings.

Although hardwoods have been used most commonly in intensive culture studies, yields of softwoods may exceed those of hardwoods on certain sites. Hardwoods are site-demanding, and the establishment of hardwoods on poor sites may be uneconomical because of heavy fertilizer and weed control requirements. Intensively cultured plantations of 7-year-old tamarack (*Larix laricina*) were found to produce 4.3 to 5.2 tons/ha annually, when planted at close spacings, fertilized, and irrigated. Under similar conditions, 7-year-old jack pine produced higher yields, ranging from 6.8 to 8.1 tons/ha annually. Optional spacings will be determined by the expected rotation age; for example, the maximum mean annual increment for the 0.23 m × 0.23 m spacings occurred at age 6 for tamarack and age 5 for jack pine. As spacing increases, the corresponding rotation age increases also.

The use of such intensive culture methods as fertilization, irrigation, and cultivation appears to be an efficient use of energy. The ratio of net energy gain to total energy utilized was calculated to be 4.3 for *Populus* and 4.7 for jack pine, with a net energy content of 306 MBtu/ha for *Populus* and 236 MBtu/ha for jack pine. When comparing the net energy ratios for intensive culture systems and naturally regenerated forests, it appears that net energy returns are linearly and positively related with the energy invested in the system. Although net energy ratios of up to 157:1 have been reported for natural forests, the energy produced annually per acre by these stands is very low. To meet future fiber and energy demands from forests, more intensive systems will have to be used, and it appears that these systems will be efficient producers of energy.

Many hardwoods will coppice or sprout from the stump after cutting thus eliminating establishment costs for the next rotation. The vigor of coppice growth will differ greatly by species and clone and must be determined in field tests.

YIELD RESPONSE TO NUTRIENT AND MOISTURE REGIMES



A traveling irrigation system is used to provide water for the large field experiments. During operation, a water turbine powered winch advances the unit along a cable anchored at one end of the irrigation lane. The unit is drawn by tractor back to the starting point at the beginning of each day that irrigation is required.

Research Problem

Conventional silvicultural practices have historically provided less than optimum nutrient and water supplies to trees, and therefore tree growth has not approached the biological potential of the species. Traditional practices reduce the number of trees on a site to allocate the fixed supply of water and nutrients to fewer trees. With SRIC systems the number of trees (spacing) is fixed at the time of planting and the problem is to determine the quantity of water and fertilizer necessary for maximum yield. Related problems are to determine the timing of fertilizer and water application and the extent to which nitrogen-fixing plants may be introduced into intensive culture plantations to reduce costly nitrogen fertilization.

Research Objectives

Gross plant nutrient and moisture requirements are known for the genera under consideration for intensive culture, but the specific requirements for promising species and/or clones are not known. The growth responses with regard to fertilizer application rate, formulation, placement, and time all must be determined experimentally. Furthermore, the interaction of irrigation and fertilization in affecting plant growth will be studied. Research in growth-room, greenhouse, and field studies will be conducted to identify the soil-water potential and nutrient levels of the plant and soil for maximum plant growth for selected clones. Also, changes in physical and chemical soil properties and ground water quality will be identified.

Research Results

A Continuous Function Design was used in field experiments, with a moisture gradient superimposed

at right angles upon a fertilization gradient. The effects of the independent variables (water and nitrogen level) and all the combinations of these two variables on the growth of hybrid poplar were thus tested on ¼-acre plot. The water was provided by a trickle irrigation system and the fertilizer, ammonium nitrate, was applied by hand. Measurements after the second year show that up to 2 inches of irrigation per week considerably increased height growth, whereas additional amounts of irrigation (more than 3 inches per week) inhibited height growth. Fertilization with 100 lbs/acre/year nitrogen as ammonium nitrate increased height growth as much as 30 percent. Additional amounts of nitrogen decreased height growth. A smaller plot with an irrigation gradient and increasing percentages of nitrogen-fixing *Alnus glutinosa* planted among the *Populus* showed that *Populus* height growth increased about the same when mixed with a large proportion of *Alnus* as when fertilizer was applied. This has significant implications for reducing fertilization costs in intensive culture systems.

A trickle irrigation system is used for precise application of water in irrigation studies. Microtubes discharge water at 4-foot intervals along the ½-inch plastic pipe. The nutrient gradient was established by hand application of fertilizer.

EFFECT OF CROWN ARCHITECTURE AND CANOPY ON YIELD

Light interception is related to both the number of leaves per tree and the leaf area per tree. Leaves of selected Populus *clones grown under SRIC may exceed 30 cm in length, and provide a large surface area for light interception.*

Problem

The amount of sunlight that leaves intercept is greatly dependent on the arrangement of leaves on the branches (crown architecture) and the density of leaves within the stand canopy. This captured light, in turn, directly affects the amount of photosynthetic activity and total biomass production. When the most advantageous leaf arrangement on branches is known, trees with these characteristics can be selected for clonal testing under SRIC.

Total biomass production in both agricultural and silvicultural systems is closely related to total leaf area of the stand. Two of the major limitations to productivity of plants are the length of time required to obtain the optimum leaf area index and the ability to maintain that optimum leaf area. The low productivity of many forest stands is partly due to the lengthy period of time required to achieve optimum leaf area. A goal of SRIC forestry is to increase the

effective leaf area earlier in the rotation and maintain it longer than more conventional forest systems.

The suitability of trees grown under SRIC for pulp production also depends partly on the distibution of biomass among tree components. Crown architecture will influence the percentage of biomass in branch and stem wood, and thus affect quality of yield for pulp and other wood products.

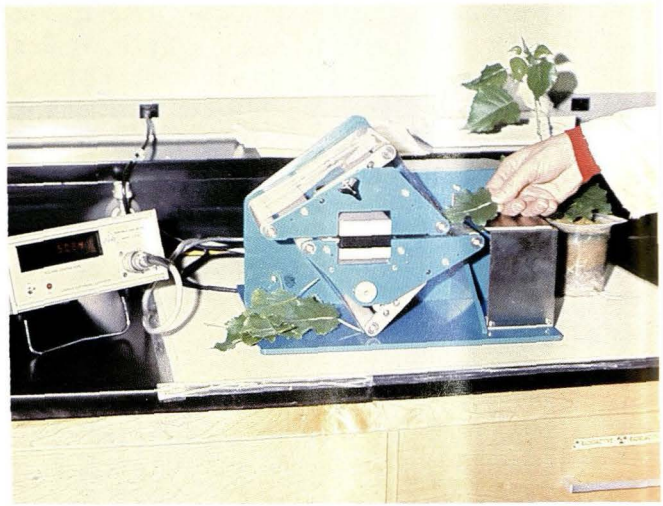
Research Objectives

The "ideal" tree for intensive culture will be further defined through studies that evaluate the effect of crown architecture and canopy density on yield. To identify these attributes, scientists will determine leaf development throughout the growing season, light interception by leaves within the stand, and affect of crown architecture on distribution of photosynthetic products within the tree. Studies will also address the affects of growth regulators on leaf production and the affect of spacing, cultural practices, and age on canopy characteristics.

Research Results

Distribution of the number of leaves per tree and the leaf area index was studied in a 5-year-old stand of *Populus* 'Tristis' grown under SRIC at 1.2 m spacing. Average leaf area index was 7.6, which is 1 to 5 times higher than reported natural stands of *Populus* in the same area. Trees contained an average of more than 6,600 leaves or 4,800 leaves per square meter. The percentage of leaf area on long shoots was 53 percent, compared to 10 to 20 percent on trees grown in native stands. Leaves on short shoots are produced early in the growing season and mature early. Long shoots produce leaves continually during the growing season, thus providing an advantage of continuous production of photosynthate throughout the summer.

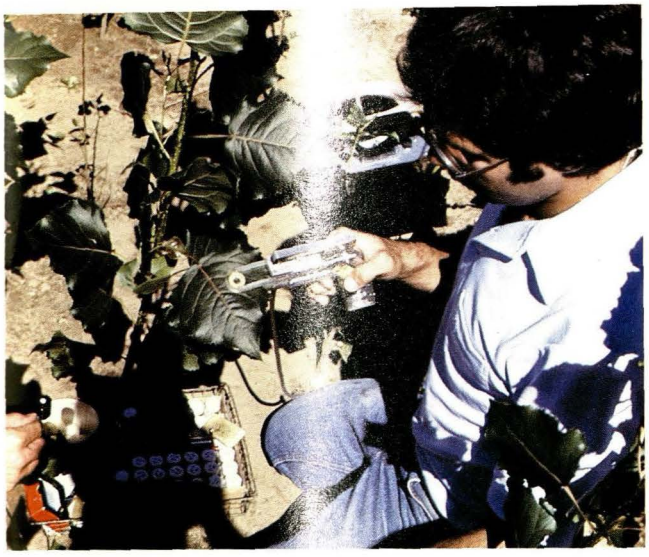
During the first 3 years, leaf area per tree and number of leaves per tree for several *Populus* clones were not affected by planting densities from 0.2 to 1.4 meters. Thus, attainment of high leaf area indices and concomitant rapid growth depends greatly on the high density of trees in the early years of establishment. In SRIC forestry leaves are concentrated on a large number of individuals rather than a few as in more conventional forests.



Leaf area index describes the surface area available for photosynthesis in forest stands and is one of the best indicators of photosynthetic capacity. Automatic measurement of the surface area of each leaf using this instrument has greatly accelerated research in this area.

Observation of the vertical distribution of leaves within the canopy showed that about 25 percent of the leaf area produced on 3-year-old *Populus* 'Tristis' was on the terminal shoot. Because photosynthates produced by the terminal shoot leaves are directly translocated to the stem, greater proportions of leaves on the terminal shoot will no doubt increase stem biomass production. The lower branches of intensively cultured trees retain their leaves longer than those of conventionally cultured trees, which results in an even greater leaf surface area for light interception. This retention can most likely be attributed to the optimum growing conditions of intensively cultured trees.

PHYSIOLOGICAL FACTORS INFLUENCING YIELD



Gross photosynthetic rates of Populus *are measured in the field using a $^{14}CO_2$ technique. Measurements of leaf conductance, leaf and air temperature, relative humidity, and photon flux density are made concomitantly to provide for the proper interpretation of photosynthetic rates.*

The CO_2 compensation point of excised Populus *leaves is measured in the laboratory. Such information about physiological responses may be used to preselect clones before expensive field screening is conducted.*

Problem

Photosynthates (mostly sugars) are produced in the leaves during photosynthesis and are then translocated to all other parts of the tree. These photosynthetic products may be used for maintaining plant processes (respiration) or for producing biomass. Therefore, the net biomass production is dependent on the rates of photosynthesis and respiration, as well as on the distribution of photosynthates among plant parts.

Numerous physiological variables have been identified through extensive agronomic research as important determinants of biomass production in crop plants, but the importance of most of these variables has not been determined for woody plants. When more information about the desirable characteristics of trees for SRIC systems is available, genetic tree improvement programs can incorporate these traits into selections.

Research Objectives

The relation between physiological variables and the quantity and quality of yield for selected trees

Populus *leaves are exposed to $^{14}CO_2$ in the field. Three days later, the whole tree will be harvested and the $^{14}CO_2$ activity will be measured in the leaves, branches, stem, and roots.*

grown under intensive culture will be studied. These variables will include rates of photosynthesis and respiration, photosynthetic efficiency, patterns of photosynthetic activity during the growing season, patterns of photosynthesis within the tree crown, and patterns of photosynthate distribution within the tree. Recommendations for selecting trees can then be based on the complex system of physiological variables know to affect yield.

The methodology for conducting physiological studies on trees in the field is not available, partly because of the size and complexity of trees. Therefore, considerable effort will be needed to develop field physiological research techniques for young intensively cultured trees.

Research Results

Field, greenhouse, growth chamber, and laboratory studies have been initiated to measure the rate of net photosynthesis, leaf conductance, and CO_2 compensation points of individual leaves at various positions within the canopy throughout the growing season. Concurrently, the translocation of photosynthates is measured by exposing groups of three fully-expanded contiguous leaves to $^{14}CO_2$. Trees are harvested after 72 hours and sampled for percentage of ^{14}C-activity in various tree components to determine the translocation of photosynthates produced during the exposure to $^{14}CO_2$. Laboratory experiments to confirm exposure and sampling methods have been completed, and as trees grow older and more complex it is expected that more sophisticated field sampling methods will be developed.

Field experiments with young *Populus* trees grown under SRIC have provided some preliminary results. The upper leaves translocate photosynthates upward for use in shoot development, the middle leaves translocate photosynthates both upward to the shoot and downward to the lower stem and roots, and the lower nonexpanding mature leaves translocate primarily downward to the lower stem and roots, where they are utilized for vascular and structural tissues. These results suggest that because mature leaves contribute mainly to stem wood production, it may be desirable to select for trees that retain mature leaves.

RAW MATERIAL QUALITY OF INTENSIVELY CULTURED TREES

Scanning electron micrograph of a tension wood fiber from short rotation intensively cultured Populus *tree. Surface dislocations (wrinkles) on the fiber affect subsequent paper strength properties (2000X).*

Problem

The value of biomass produced under SRIC systems depends primarily on the type of specific products for which it can be used. Because wood is such a versatile raw material, an integrated research program must consider the value of wood produced under intensive culture for a wide range of current products as well as those that may be demanded in the future.

Intensive culture practices influence physiological processes which in turn affect the anatomy, chemical composition, and physical properties of the raw material and therefore the usefulness of the material.

Research Objectives

The effect of such variables as plant material, spacing, fertilization, moisture regimes, and age on the quality of raw material will be determined. Tests will be made to measure the suitability of raw material produced by SRIC (including bark) for pulp and paper, particleboard, fiberboard, chemical feedstocks,

energy, and animal feed. For the purposes of genetic selection and breeding programs, the most desirable raw material attributes for trees grown under intensive culture will be identified.

Research Results

The energy content of most woods is similar—hardwoods average 4,400 and softwoods average 5,000 kcal per kg of ovendry wood. The factors that contribute to differences in energy value of wood are the moisture content, density, and the ease of drying before conversion. Density will also affect transportation costs and may affect rates of conversion. Tests of juvenile *Populus* wood grown under SRIC have shown that moisture content and density are not significantly different from wood grown under conventional systems.

Wood quality may be important in indirect energy conversion processes and for the utilization of wood as liquid fuel and chemical feedstock. For example, lignin may hinder the conversion process, and appropriate plant selections could be made for genotypes with low lignin contents. When conversion processes and wood quality needs for these processes are better defined, research in this area will be more appropriate.

The primary concerns associated with the use of rapidly grown juvenile wood for pulp and paper are that high percentges of bark may be present in whole-tree chips and that juvenile wood has shorter fibers than mature wood, which can adversely affect pulp yields and paper strength.

Most anatomical characteristics vary greatly by species and clone and thus are important selection factors that affect utilization. Anatomical studies have generally shown higher percentages of spring wood and transition fibers in wood grown under SRIC; this fact is probably the reason for lower specific gravities for conifer wood grown under intensive culture. Intensive culture jack pine and larch fibers were only one-third as long as fibers from older mature wood, but improved pulping processes have made fiber length less important. However, more reaction wood is produced under intensive culture than under conventional silvicultural practices probably due to the accelerated growth rates.

In one study pulp yields of tension wood and normal wood were 60 and 53 percent, respectively. Al-

Trees from the first SRIC plots are used for a multiple of research purposes. After they are weighed to determine total above-ground biomass yield, the wood is used in utilization tests.

though paper from tension wood had inferior strength properties to that from normal wood, the properties of kraft paper produced from SRIC *Populus* are still within acceptable ranges. Tension wood fibers resisted collapse during beating and produced a thicker, more porous sheet, but the pulp was still clearly acceptable after refining.

Wood produced from 8-year-old jack pine and larch grown under SRIC was also found to be acceptable for kraft pulping, with 41 percent pulp yield for jack pine and 39 percent for larch. On the basis of handsheet strength tests including burst, tear, and tensile, larch was slightly superior to jack pine. The acceptability of *Populus* and the conifer raw material produced under a SRIC system differed little. Thus, it was concluded that biomass yield and clonal differences are the major factors for determining the most promising species and clones for SRIC.

Wood produced under intensive culture has been found to be acceptable for kraft pulping. The wood may also be suitable for thermomechanical pulping.

Wood grown under SRIC was also tested in thermomechanical pulping processes, which offers the advantages of higher yields and lower capital investments than kraft pulping. Tests showed this wood to be inferior to pulps obtained from mature wood because fiber lengths were shorter; fiber length is more critical for obtaining paper strength for thermomechanical pulps than for kraft pulps. However, optical properties were generally good, which suggests that blending of mechanical and kraft pulp may be possible. Bark content was a major factor in the lower performance of SRIC produced wood, which could be decreased by longer rotations and improved methods of whole tree chip segregation.

This whole-tree chipper automatically separates some of the foliage from the chips. The chips may be further separated by the Vacuum Airlift Segregation process.

Intensive cultured *Populus* may also be suitable as a raw material for producing flakeboard, a structural particleboard. Tests on five *Populus* clones showed clonal variation in board strength properties, with the better clones producing boards exceeding industrial guidelines for strength properties. Bark reduced board strengths much less than was expected.

Another alternative use for Populus foliage is animal feed supplement. Recently matured Populus leaves have been found to contain levels of nitrogen, carbohydrates, and pigments comparable to forage crops. Feeding tests with ruminants showed the foliage to be acceptable, although the palatability of clones differ.

To alleviate the problems resulting from high bark content in the manufacture of both reconstituted wood products and pulp and paper, a vacuum airlift segregation (VAS) process was developed to separate whole tree chips into components— wood chips, bark, foliage, and fines. In the VAS process, chips are spread over a continuously moving wire mesh conveyor belt that passes under a series of vacuum hoods, which separates the components on the basis of differences in terminal settling velocities of the particles.

Populus *foliage has been found to be acceptable ruminant feed, although the palatability appears to vary by clone.*

Processing systems such as the VAS offer numerous alternatives for the utilization of the biomass, depending on the market demands and industry objectives. Four single- and multiple-use alternative systems are summarized below for 5-year-old *Populus* grown under SRIC at 1.2 m spacing.

System	Pulp yield *Metric ton/ hectare*	Energy *M kcal/ hectare*	Feed *Metric ton/ hectare*
Pulp only	42	—	—
Energy only	—	200	—
Pulp and energy	27	68	—
Pulp, energy, and animal feed	27	48	5

DISEASES OF INTENSIVELY CULTURED SPECIES

Leaf rust causes defoliation of Populus *before the end of the growing season. As shown, severity of damage varies between clones so selection will be made for those clones that are least susceptible to leaf rust.*

Research Problem

Intensive culture systems may be more vulnerable to disease than conventional mixed species stands because they contain only a few species or hybrids and they may facilitate transmittal of pests because they are closely spaced. At any rate, the susceptibility of a species to pests and the possible control methods must be determined before any species or clone is widely planted.

Research Objectives

It is well known that *Melampsora medusae* leaf rust, *Marssonina brunnea* leaf blight, and *Septoria*

musiva Peck leaf spot and canker are the most prevalent poplar diseases in the United States. The susceptibility of various *Populus* clones to these and other diseases will be determined through this research. Additionally, the incidence and severity of these diseases within the north-central region of the United States will be examined. Integrated control methods to reduce damage from these diseases will be recommended.

Research Results

The screening of clones for disease susceptibility throughout the intended establishment range is extremely important. *Populus* clones were planted at each of 13 sites throughout the Midwest in 1976 and 1977, with an intent to monitor the plots for 10 years. After one growing season, it was found that the most serious diseases were *Marssonina* leaf spot, *Melampsora* leaf rust, *Septoria* leaf spot, *Cytospora* canker, and *Septoria* canker. The severity of each of the diseases varied widely in the region.

Leaf rust injures trees by causing leaf damage and defoliation, and when severe, increases susceptibility to other diseases. Incidence was found to vary greatly between clones, and fungicide treatment delayed defoliation but did not prevent severe rust damage for one hybrid, *P. deltoides* x *P. balsamifera* 'Northwest'. Infection is usually most severe on lower leaves, thus it generally affects basal diameter growth but not height growth.

INSECT PROBLEMS IN INTENSIVE CULTURE

Research Problem

Because intensive culture crops are expected to be fairly uniform in species, age, spacing, and genetic composition, the potential for insect outbreaks may be greater than in forests with a wide range of species and ages. However, the SRIC system affords the opportunity of using cultural tools to control insects before they become destructive.

Natural enemies of *Populus* include more than 150 insects. The most destructive of these are leaf aphids, which feed on leaves and ultimately defoliate the trees. Jack pine and larch also have numerous defoliating, sapsucking, and shoot-stem boring insect pests.

Research Objectives

Insect damage depends on the number of insects attacking the tree or stand, the part of the tree infested, the season of attack, and the age of the tree. After the potential insect pests are identified, clones resistant to these pests may be selected, although resistance includes extremely complex factors such as nutritional status and vigor of the tree.

Control methods for insects in intensive culture systems will be identified. These may include site preparation to eliminate insect habitats occupied in other stages of the life cycle, fertilization to improve nutritional status of the tree or alter tissue components essential for specific insect pests, irrigation to eliminate the water stress conditions that are often causes of insect outbreaks, and hybridization to alter plant density. Close planting may provide stress from competition or modify environmental conditions to limit some insects and favor others.

Research Results

Insect damage has been surveyed on established intensive culture plots of *Populus* throughout the North Central States. Aphids, *Chaitophorus populitoliae* (Oest.), were found to cause the greatest defoliation damage, although considerable differences in severity of attack were observed among clones.

Further tests on the impact of defoliation in relation to clone and spacing have begun. An experiment to test the effects of various degrees and timing of defoliation on yield is in progress— certain percentages of leaves are manually removed at various times during the growing season. The effects of girdling and boring damage will be determined in similar experiments by physically damaging the trees. When the season and severity of impact can be related to actual yields, cultural control methods will be prescribed.

DESIGN OF MECHANIZED EQUIPMENT FOR INTENSIVE CULTURE SYSTEMS

This tree planter was modified for planting unrooted cuttings. The operators place the 8-inch cuttings vertically in a trench and the planter wheels pack the soil around them.

Research Problem

Labor costs are rising in all sectors of the economy, and forest and agricultural operations have become increasingly mechanized in order to lower production costs. Intensive culture systems must also be mechanized. Although they require many cultural operations widely practiced in agriculture, commercial agricultural equipment is generally not suitable for tree crops.

Researchers have improvised equipment for planting cuttings, cultivating, and irrigating. Small research plots have been harvested with chain saws. Yet these methods will be impractical for even the large-scale pilot plantings already established. Harvesters used for current silvicultural operations are not suitable for closely-spaced stands, which have small stems and multiple stems on each stump after the first rotation. An entire systems approach must be developed for harvest, collection, and delivery of wood to the pulp mill or energy conversion facility.

Research Objectives

Modifications of commercial agricultural and horticultural equipment will be investigated first, although substantially different equipment for intensive culture systems may eventually be developed if these modifications do not perform satisfactorily. In particular, equipment needs for planting, cultivation, fertilization, and irrigation will be assessed.

Probably the most critical need is for appropriate harvest equipment. Design criteria for a small-diameter short-rotation harvester are currently being developed, and preliminary designs for the cutting head are already underway.

Research Results

Engineers working with this program have modified existing tree planting equipment to accommodate the large unrooted and rooted cuttings used in the large-scale field plantings. These modifications are currently being tested in the field and will be further improved as operational data are obtained. Similarly, a traveling irrigation system to deliver water over 3 to 9 m-high trees has been installed for the large field plantings. The irrigation system performance will be critical as the trees increase in height toward 9 m or taller, because the system must be able to deliver water uniformly over the land area.

Preliminary design criteria have been developed for the mechanized harvest equipment. In general, it must be capable of harvesting one or more rows of the plantation at one time, severing each tree sequentially in the row, and forwarding the material to the landing site. The lack of information about optimal spacings and rotation age (and thus stem diameter and height) make the design efforts and equipment development a continuous process. Consequently, it is highly unlikely that the first generation of small-diameter harvesters developed will be those which are ultimately commercially produced.

To ensure an acceptable level of regeneration by coppicing, the harvester must make a clean cut surface and provide minimal pressure against the stumps and root systems. It must be able to cut at low stump heights and handle the multi-stem tree that will develop in coppice rotations of hardwoods. The wood will probably be used as chips, so the harvester must simultaneously chip the wood or a whole-tree chipper must be present at the landsite. Existing chip trucks will be suitable for final transport of chips to the mill or conversion site.

COST OF PRODUCING WOOD FOR FUEL AND FIBER

The effectiveness of herbicides in reducing weed competition (left) compared to the control (right). When large field tests are conducted for such intensive culture practices as weed control, the costs and effectiveness of alternative treatments can be compared.

Research Problem

SRIC systems have been explored in response to rising land prices and taxes, increasing demands for recreation and nonforest uses of forest land, escalating future fiber demands, and rising costs of conventional energy. The system appears to offer resource managers the opportunity to supply the same quantity of fiber on much less acreage and the opportunity to grow energy feedstocks at competitive prices. An additional significant attraction of this system is the potential realization of an equivalent return on investment with 6 to 10 years after planting, rather than the 30 to 60 years necessary for conventional silvicultural systems.

Before intensive culture management will be widely accepted by land managers, however, detailed information on the production costs and anticipated revenues must be obtained. Estimates of the economic feasibility of intensive culture systems for fiber and fuel are needed to compare with conventional silvicultural systems for fiber and alternative energy supplies, such as coal. Although only preliminary economic analyses can be made with the information now available about yields under specific treatments, the sensitivities of the final production costs to various cultural treatments are needed by research scientists.

Until basic SRIC growth information under specific treatment regimes is readily available, economic evaluations will be partially made by using a break-even analysis technique. Break even analysis permits the physical yields (e.g., dry tons per acre) or financial yields required to cover all costs included in a specific production schedule to be estimated. In addition, the sensitivity of total production costs to individual costs such as land rent, stand establishment, fertilization, irrigation, and harvesting will be determined.

As better biological growth information and production management inputs are obtained from larger-scale plantings, more sophisticated economic analyses for calculating present net worth and internal rates of return will be incorporated into the evaluations. For example, cashflow analyses will be used to calculate costs and benefits of growing *Populus* 'Tristis #1' for two 10-year rotations and three spacings, with emphasis on impacts of different interest rates, inflation and price trends, and Lake States land use alternatives.

The cashflows will be contrasted with energy flows to determine cost-energy tradeoffs. In addition, the minimum operational size will be identified. The costs and energy balances will be assessed for biomass on the stump, delivery of whole-tree chips at 100 percent moisture content, and delivery of kiln-dried whole-tree chips.

Research Results

Break-even analyses were prepared for each of eight management alternatives ranging from 2-year rotations with numerous coppice harvests to 15-year rotations without coppicing. Low, medium, and high cost estimates were used for each production activity within each of the eight management programs. All management costs were compounded to the time of harvest or the end of the rotation. These are the minimum values that must be recovered when selling the wood before any profit is returned.

Using recent simulation biological growth results and assuming that energy from wood is worth $1.00 per million Btu's and dry fiber is worth $30.00 per ton, the eight management alternatives were evaluated for potential profitability. Alternatives with rotation ages of 10 to 15 years, one coppice rotation, and average yields of 8.4 to 10.0 dry tons/acre (18.8 to 22.4 mt/ha)/year total biomass, appeared potentially profitable for both energy and fiber. The cost of wood produced under 4- to 5-year rotations approached $1.00/mmBtu and $30.00 dry ton only where low management costs were assumed. In general, the analysis suggests that the longer rotations will be more profitable than extremely short ones.

Because production costs are different between the first harvesting period and the following coppicings, the time required to recover the investment, i.e., when compounded yields exceed compounded expenditures, is also an important consideration. The farther into the future the payback occurs from initial point, the greater the risk of the investment and the more important the success of scheduled coppicings.

Evaluating the sensitivity of total production costs to changes in various cost factors provides considerable information for setting research priorities. Emphasis should be placed on cultural practices that will most decrease the total production costs if their costs were decreased. For example, a $10/acre decrease in fertilizer cost would decrease the cost of energy by $0.20/mmBtu; a $10/acre decrease in harvest costs would decrease the cost of energy by $0.15/mmBtu; and a $10/acre decrease in first-year establishment costs would decrease energy costs by $0.08/mmBtu. This result suggests that costs could be significantly reduced if fertilizer requirements were decreased by planting nitrogen-fixing cover crops, alder, or other nitrogen-fixing tree species.

More detailed economic evaluations using cash-flow analyses are in progress. Operational information on machine production rates, man-hours, and fuel consumption rates have been collected from the large-scale plantings at the Harshaw farm near Rhinelander, Wisconsin. Data will also be available from the pilot-sized intensive culture system now established in the Lake States. Costs and energy requirements have been compiled for the purchase and maintenance of equipment, and the cost curves and energy inputs for alternative equipment combinations are being developed.

INDUSTRIAL COOPERATORS

Populus *grows well on sandy sites irrigated with secondary pulp mill effluent.*

Research Problem

Industry will ultimately determine the commercial success of intensive culture concepts. Some of the intensive culture techniques developed under research conditions may not be feasible in large industrial woodlands programs. Therefore, it is extremely important to cooperate with industrial foresters throughout the research and development effort.

Research Objectives

The technical and economic feasibility of intensive culture cannot be determined by small field experiments such as those conducted at Rhinelander. Large plantations must be established to learn whether research results can be applied in industrial forest operations and to obtain information about the cost of operational intensive culture systems.

More than 30 million gallons of effluent are produced daily by a large modern paper mill in the Lake States. Currently, holding ponds are used for biological treatment of wastes before discharge into a river.

Research Results

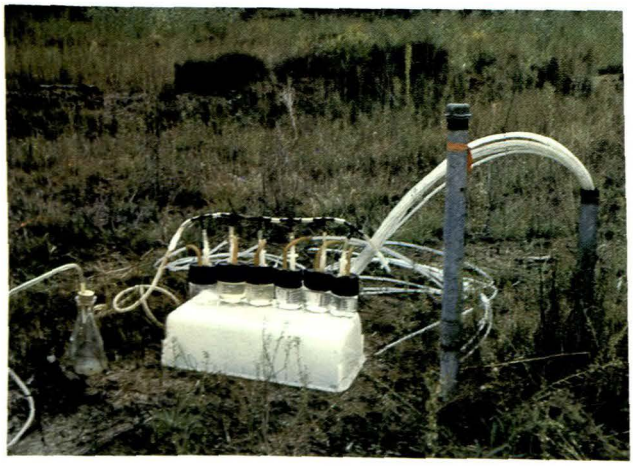
One of the pulp mills in the Lake States has been exploring the possibility of using mill effluent from a secondary treatment plant as an irrigating medium on trees growing on land adjacent to the mill. The company is interested in obtaining uniform high quality wood and in reducing transportation costs, harvesting costs, and taxes on vast acreages of forest land.

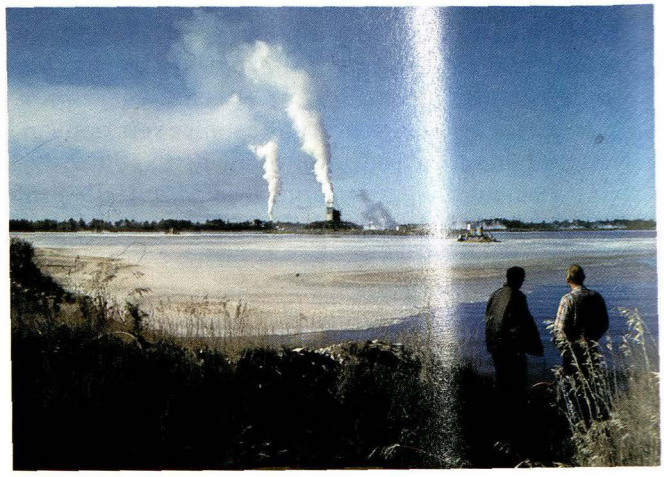
Moreover, the company is concerned about developing a means of disposing of some 30 million gallons of effluent a day, which is presently treated and then discharged into a river. One possible use for this effluent is irrigation of intensive culture trees. In areas of the United States where water is limited and industrial plants have to find a way to dispose of effluent, irrigation with treated effluent may be a solution to both problems.

A large-scale pilot study is in progress to test the most intensive methods for growing fiber. A 40-acre site has been cleared, and tilled, and *Populus* cuttings will be planted at two spacings. An irrigation system to distribute the effluent will be installed to maintain an optimum moisture regime for the trees. In addition, a 1-acre test plot of willow (*Salix*) and several *Populus* clones has been established to determine the tolerance of these species to high applications of effluent and the effect of the effluent on groundwater quality.

The groundwater at the site has been thoroughly mapped to identify depth, direction of flow, and chemical nature. Throughout the study it will be monitored to detect changes due to irrigation with the effluent.

Water sampling probes are used to monitor the groundwater quality under and near the site where effluent is being applied.

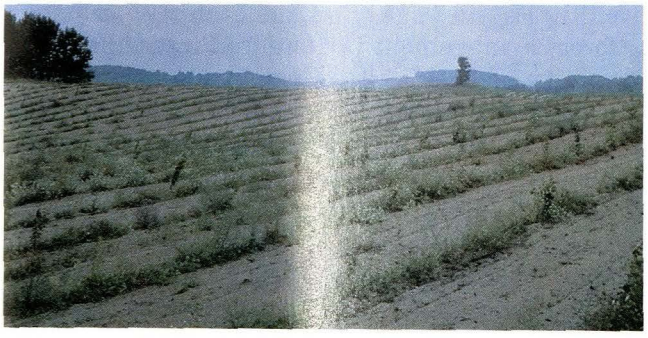




Wastewater effluent from the pulp mill holding ponds (top) is pumped (middle) to the experimental fields. There, it is applied onto the intensive culture Populus *with a flood irrigation system (bottom). Flood irrigation is used to avoid the possible odor problems of overhead spraying.*

As a separate effort, more than 1,200 acres of *Populus* and *Alnus* were planted in 1978 by the Packaging Corporation of America near Manistee, Michigan, in cooperation with the Maximum Yield Program. Nurseries of superior clonal material were established and hardwood cuttings were planted in 3.3 x 3.3 m spacings. Agricultural techniques and equipment were used to mechanically prepare the site, fertilize, and cultivate. Smaller acreages were established during the previous 3 years, with considerable failure due to stand establishment problems and weed competition. Successful cultural practices for many of these problems have gradually been worked out and survival of trees for 1978 was more than 80 percent. It is expected that an additional 1,200 acres will be established in 1979.

Commercial agricultural equipment is used for site preparation. In some fields, the mills' sewage sludge was applied to provide soil amendments.



Large plantings have been established by Packaging Corporation of America to obtain operational and economic information about meeting their mill needs with intensively cultured Populus.

At the Packaging Corporation of America plantations, a 20-foot cultivator is used to clean three rows of Populus *at one time. About 100 acres can be cultivated daily during the first growing season.*

Some of the older plantings are growing well, particularly this stand of 2-year-old Populus. *Wide spacings were used because the trees will be grown for 10-to 15-year rotations.*

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Since 1971 there has been significant progress in greatly increasing yields of wood and energy (biomass) from intensively cultured plantations compared with natural stands. This publication reports the results of studies and summarizes the "maximum-yield" research in progress at the North Central Forest Experiment Station.

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